

3D Magnetospheric Simulations with the MHD-EPIC model

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MHD-EPIC in a Nutshell

The goal is to combine the efficiency of the global (extended) MHD code with the physics capabilities of the local PIC code!

M MHD code - BATS-R-US

- Solves the ideal, resistive, Hall, two-fluid, multi-ion, anisotropic ion pressure MHD equations on 1, 2 or 3D **block-adaptive Cartesian and non-Cartesian grids**
- Explicit and implicit time stepping, up to 5th order accurate schemes
- Complicated initial and boundary conditions, variety of source terms

M PIC code - IPIC3D

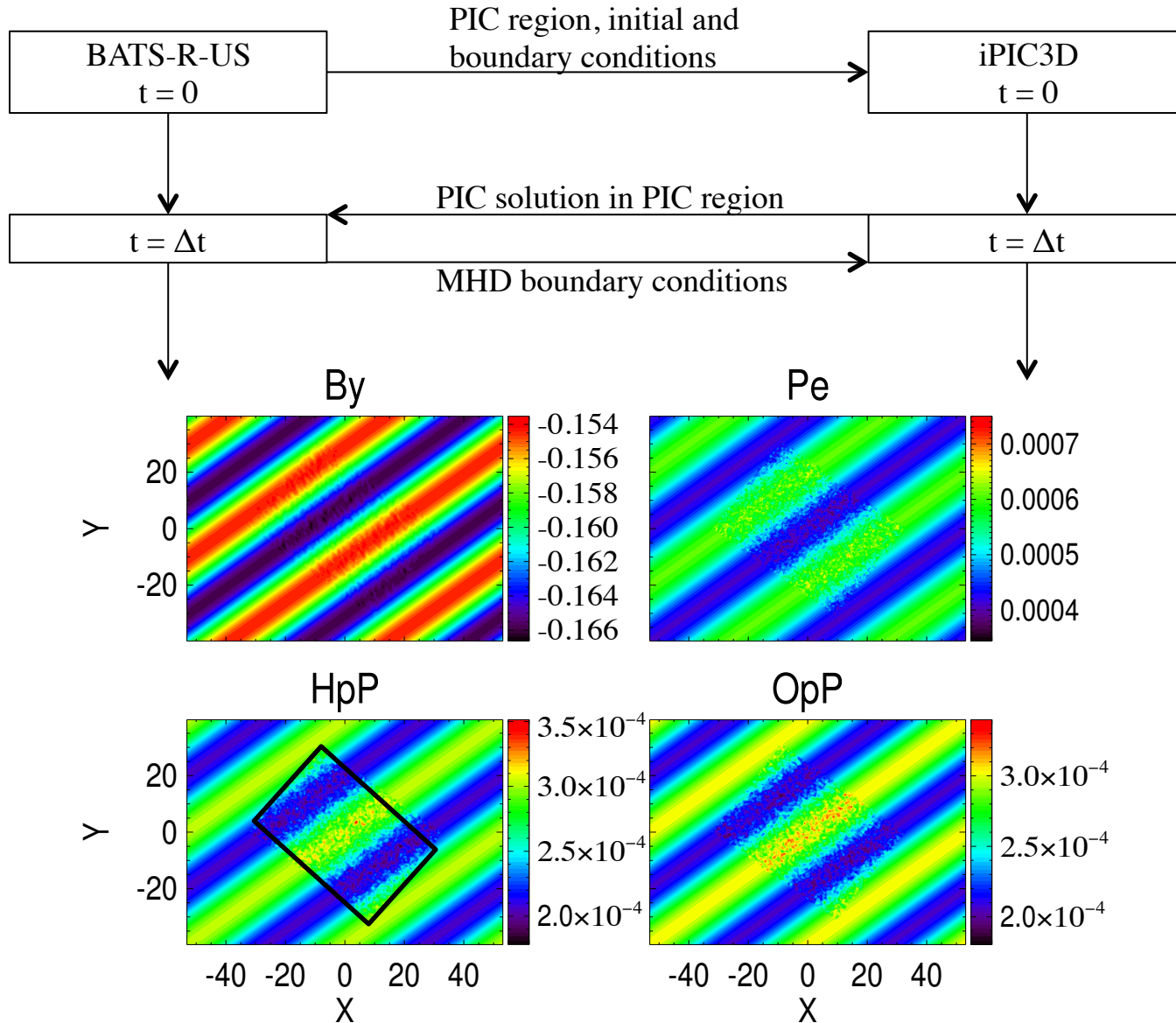
- Solves full set of Maxwell's Equations implicitly on **3D Cartesian grid**
- Equations of motion for electrons and ion species
- Collisionless plasma

M Framework – SWMF

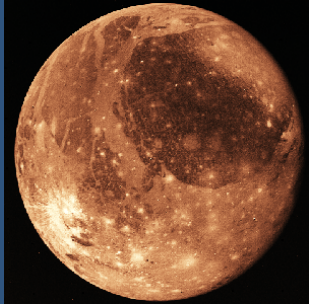
- Executes and couples multiple models on massively parallel machines
- Efficient parallel coupler developed for MHD-EPIC algorithm
- Multiple PIC domains



MHD-EPIC Algorithm

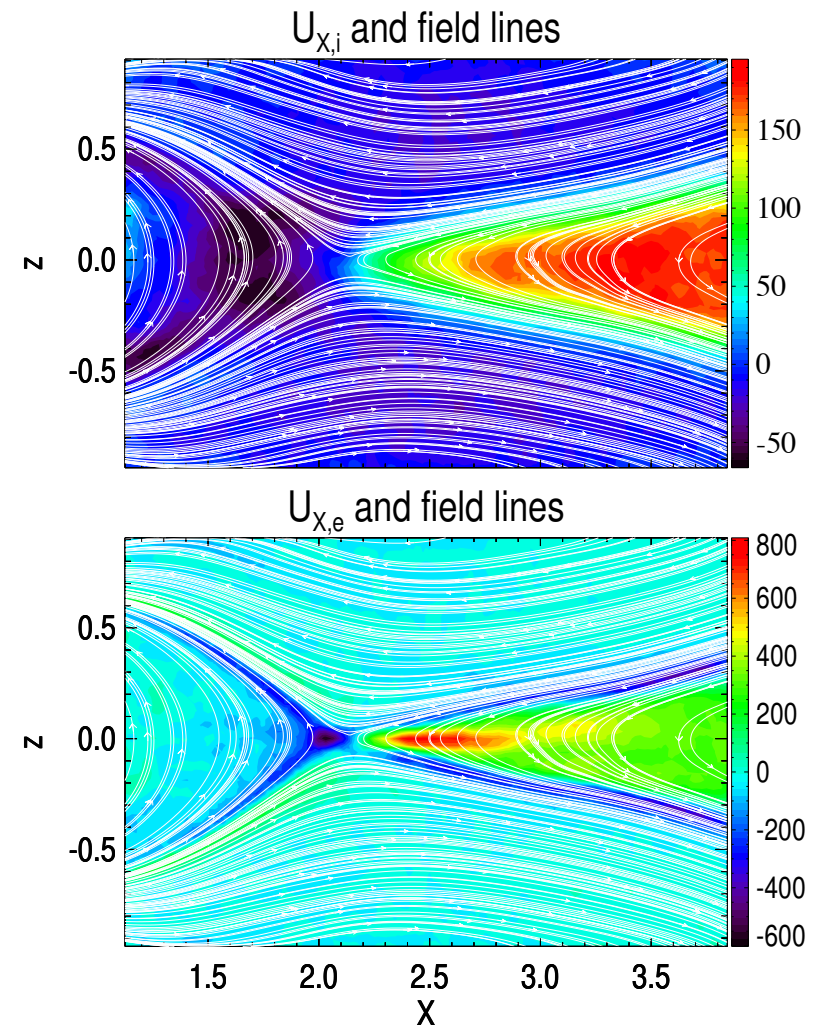


MHD-EPIC applied to Ganymede's Magnetosphere



M Ganymede is a nice initial application

- Short time scale: minutes
- Small system size compared to ion inertial length: $d_i \sim 0.16 R_g$
- For $M_i/M_e = 100$ the electron skin depth is $d_e \sim 0.016 R_g$
- Figure shows the ion and electron jets in the tail PIC region with $0.03 R_g$ grid resolution: the electron jet is reasonably well captured which indicates true kinetic reconnection in the simulation.
- Galileo measurements for validation.

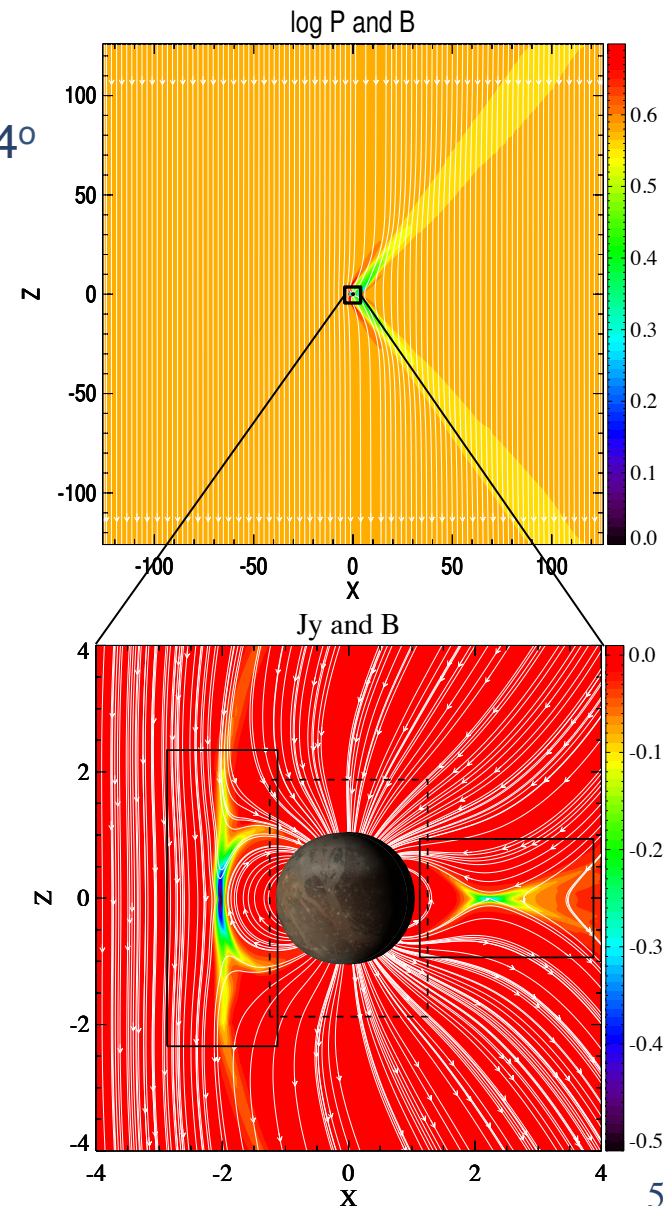




3D Ganymede simulation with Hall MHD-EPIC



- Ganymede parameters:
 - $R_g = 2634$ km, dipole strength -719 nT, tilted by 4.4°
- Jupiter wind (sub-sonic and sub-Alfvenic)
 - $n = 4/cc$, $M_i = 14$
 - $V_x = 140$ km/s, $B = (0, -6, -77)$ nT, $p = 3.8$ nPa
- Hall MHD domain: $-128 R_g < x, y, z < 128 R_g$
 - Fix values at inflow and outflow boundaries
 - Absorbing boundary condition at $1 R_g$
 - Finest grid resolution $1/32 R_g \sim 0.2 d_i$ within $-3 < x < 4$, $-3 < y < 3$, $-2 < z < 2$
 - Coarsest grid cell size $4R_g$, about 8.4M cells total
- 4 embedded PIC regions surrounding the moon
 - $1/32 R_g \sim 0.2 d_i$ resolution: 3.6M total
 - 216 macroparticles per species per cell: 1.5B total





Comparison of Density and Pressure



Hall MHD

MHD-EPIC

Hall MHD

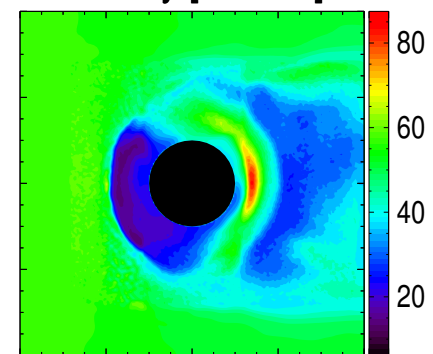
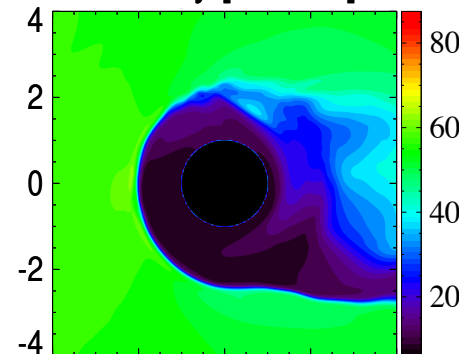
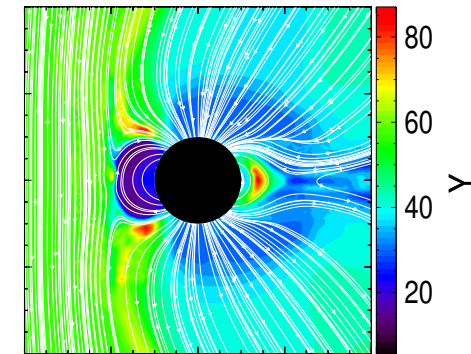
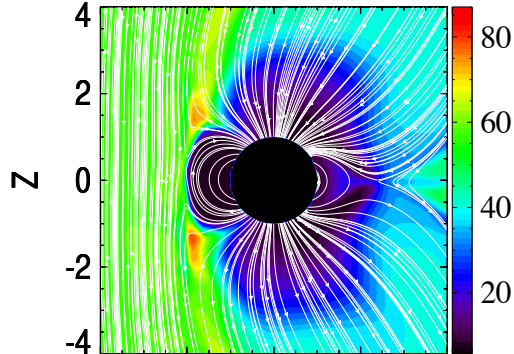
MHD-EPIC

Density [amu/cc] and B

Density [amu/cc] and B

Density [amu/cc]

Density [amu/cc]

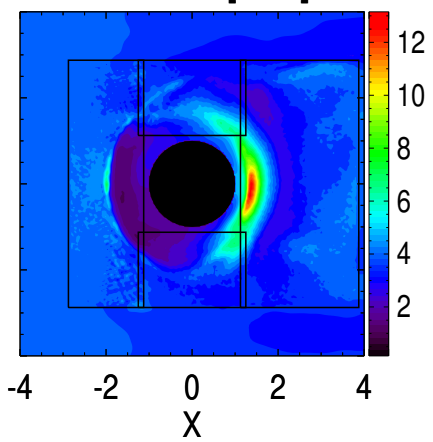
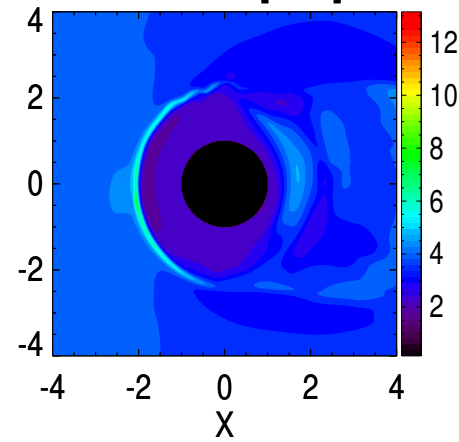
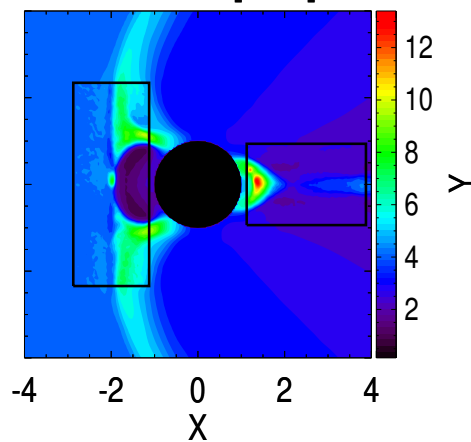
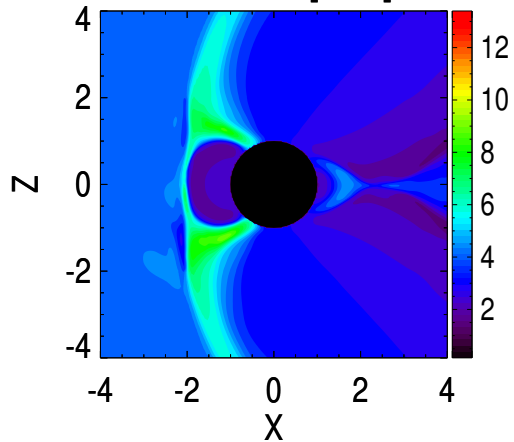


Pressure [nPa]

Pressure [nPa]

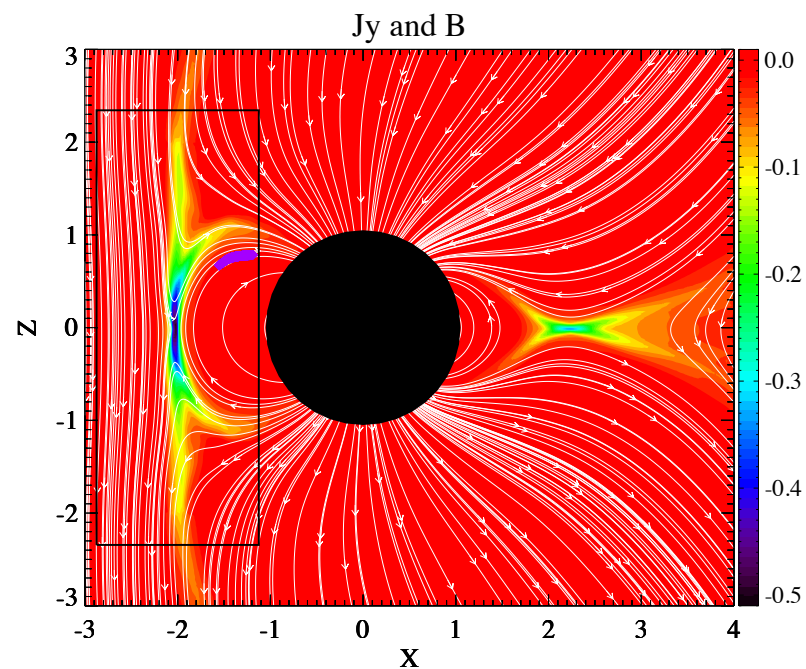
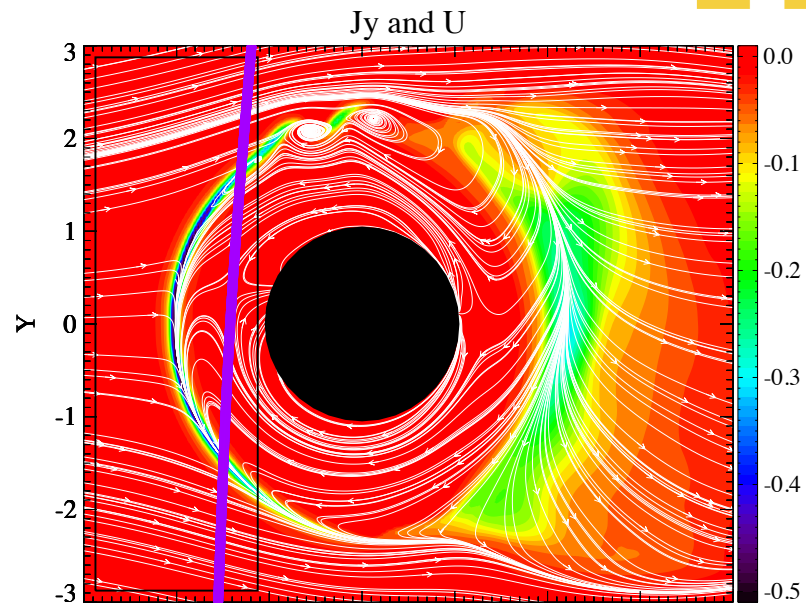
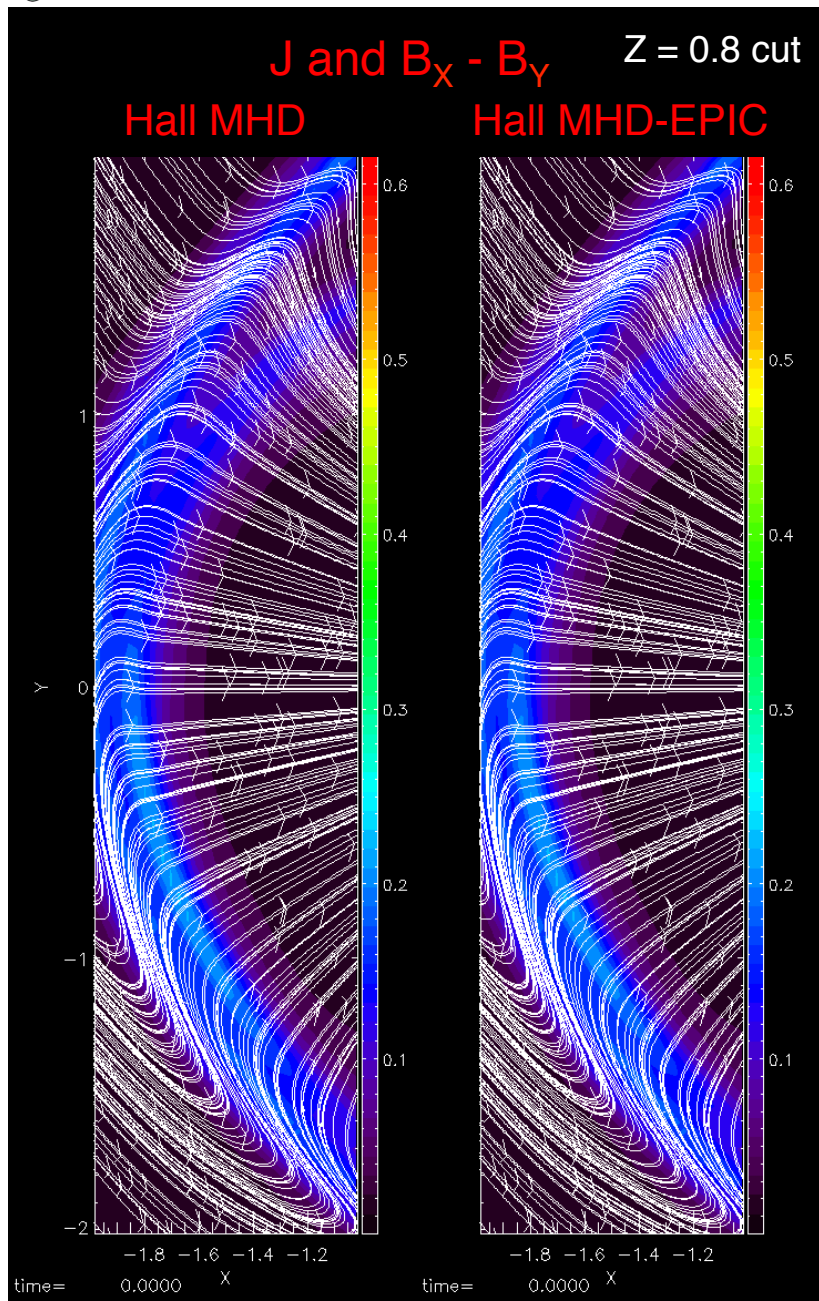
Pressure [nPa]

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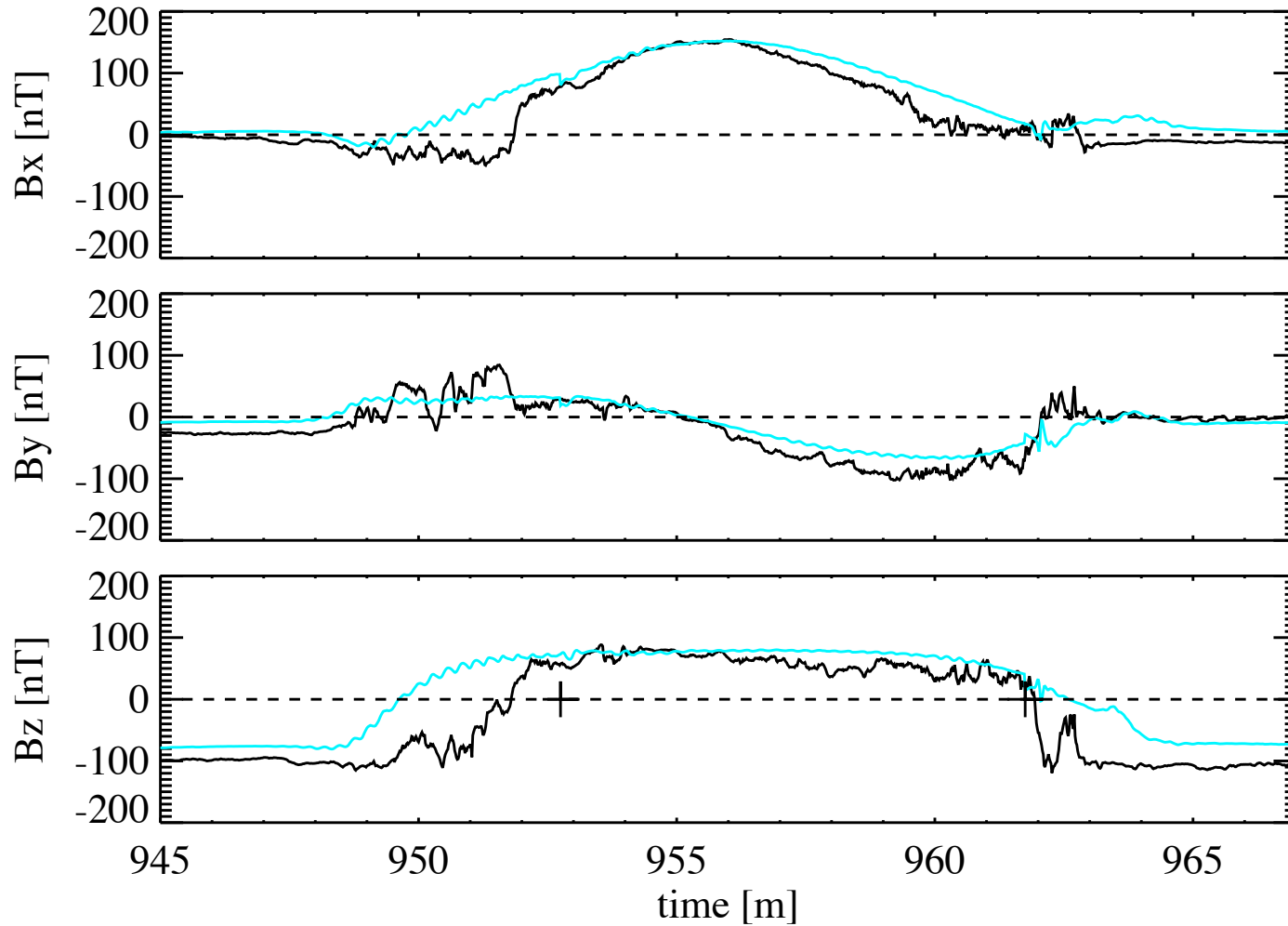


Galileo Flyby





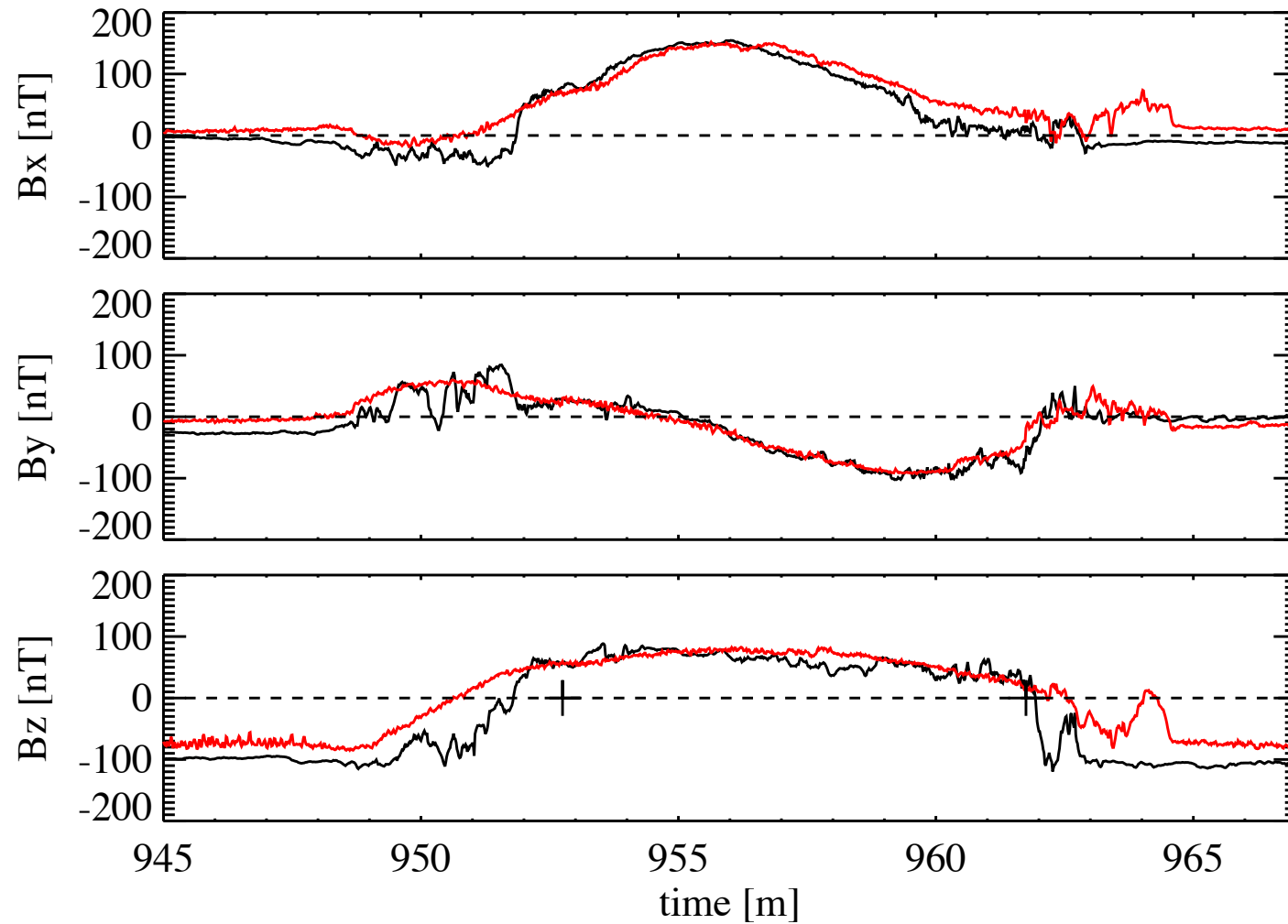
Galileo data - Hall MHD



Galileo orbit is stretched by 6% (compensates small error in standoff distance)



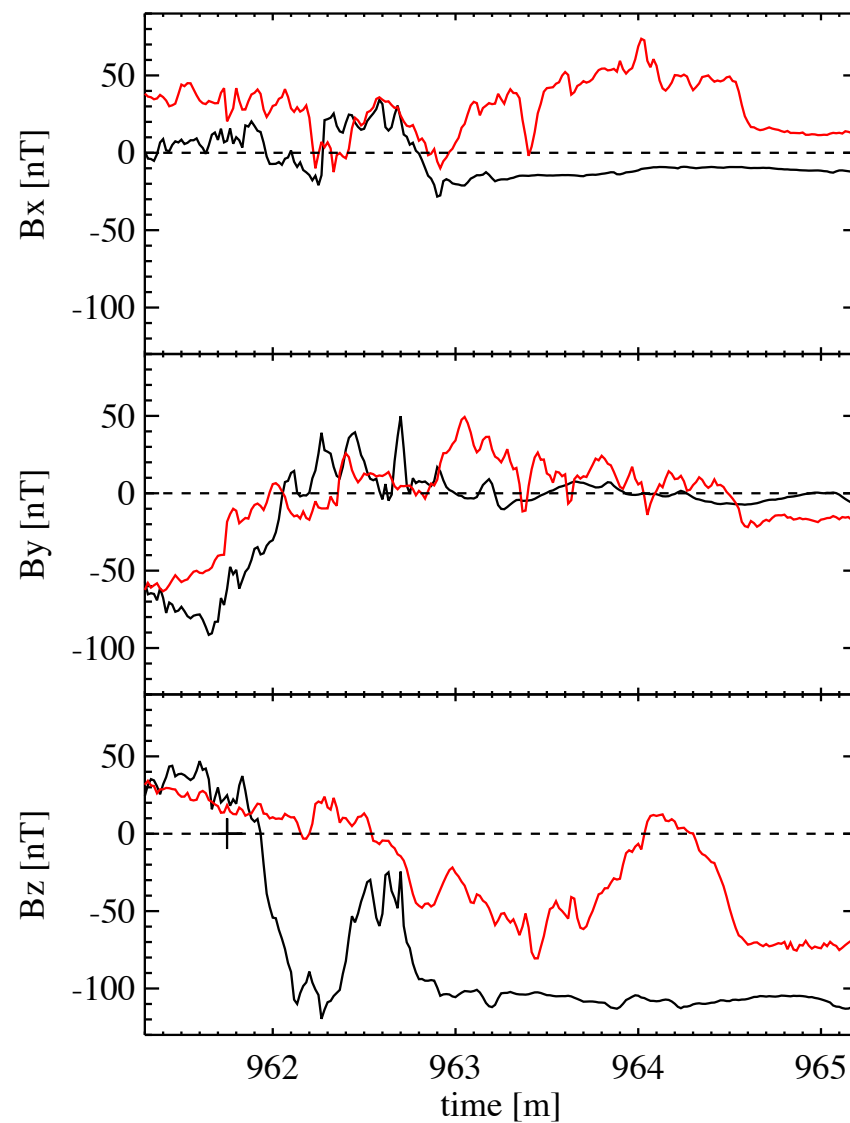
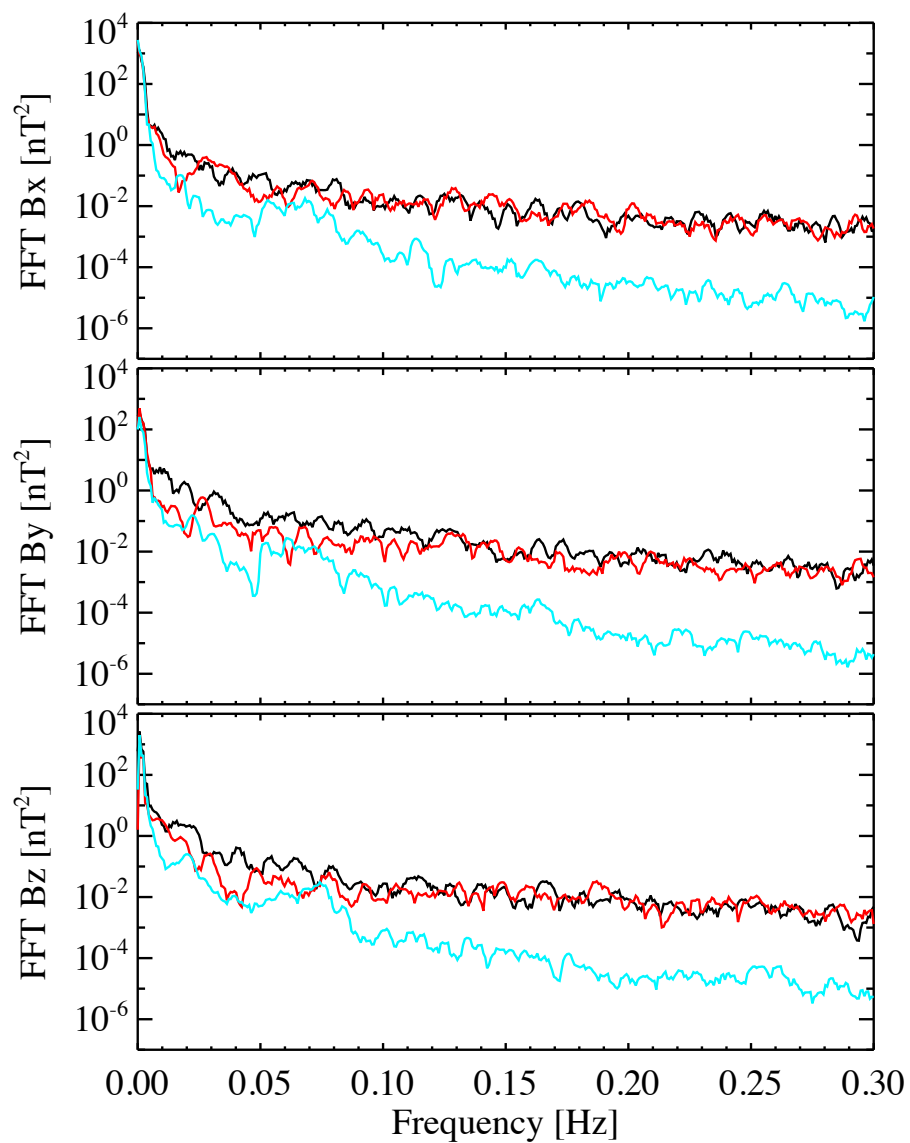
Galileo data - MHD-EPIC



Galileo orbit is stretched by 6% (compensates small error in standoff distance)

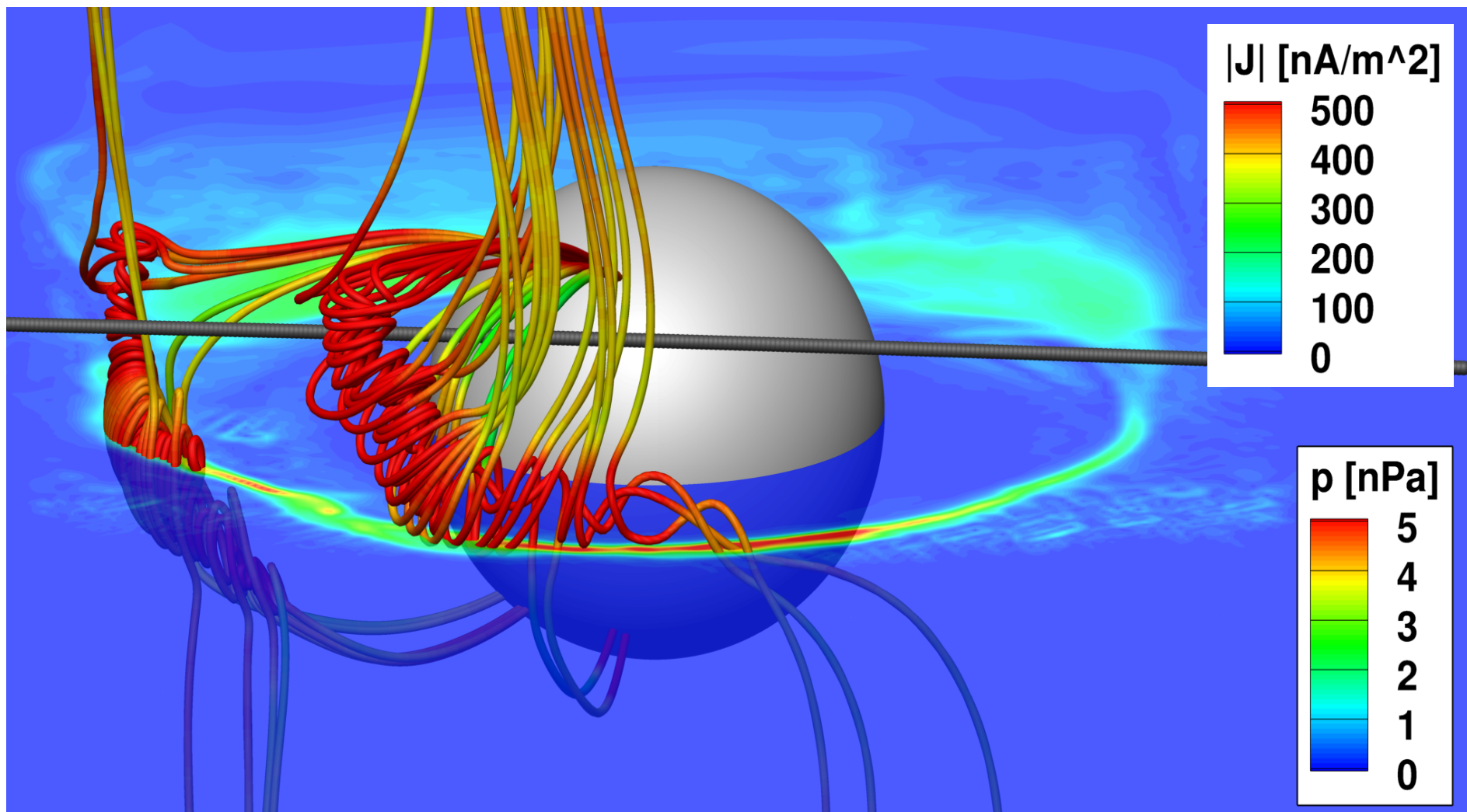


FFT and FTE





Is it really an FTE?



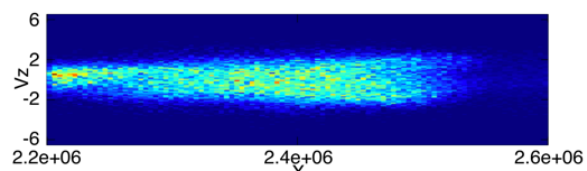
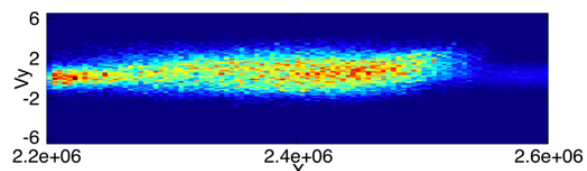
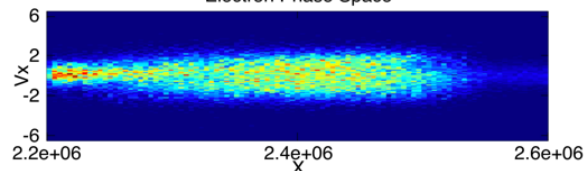
Yes!



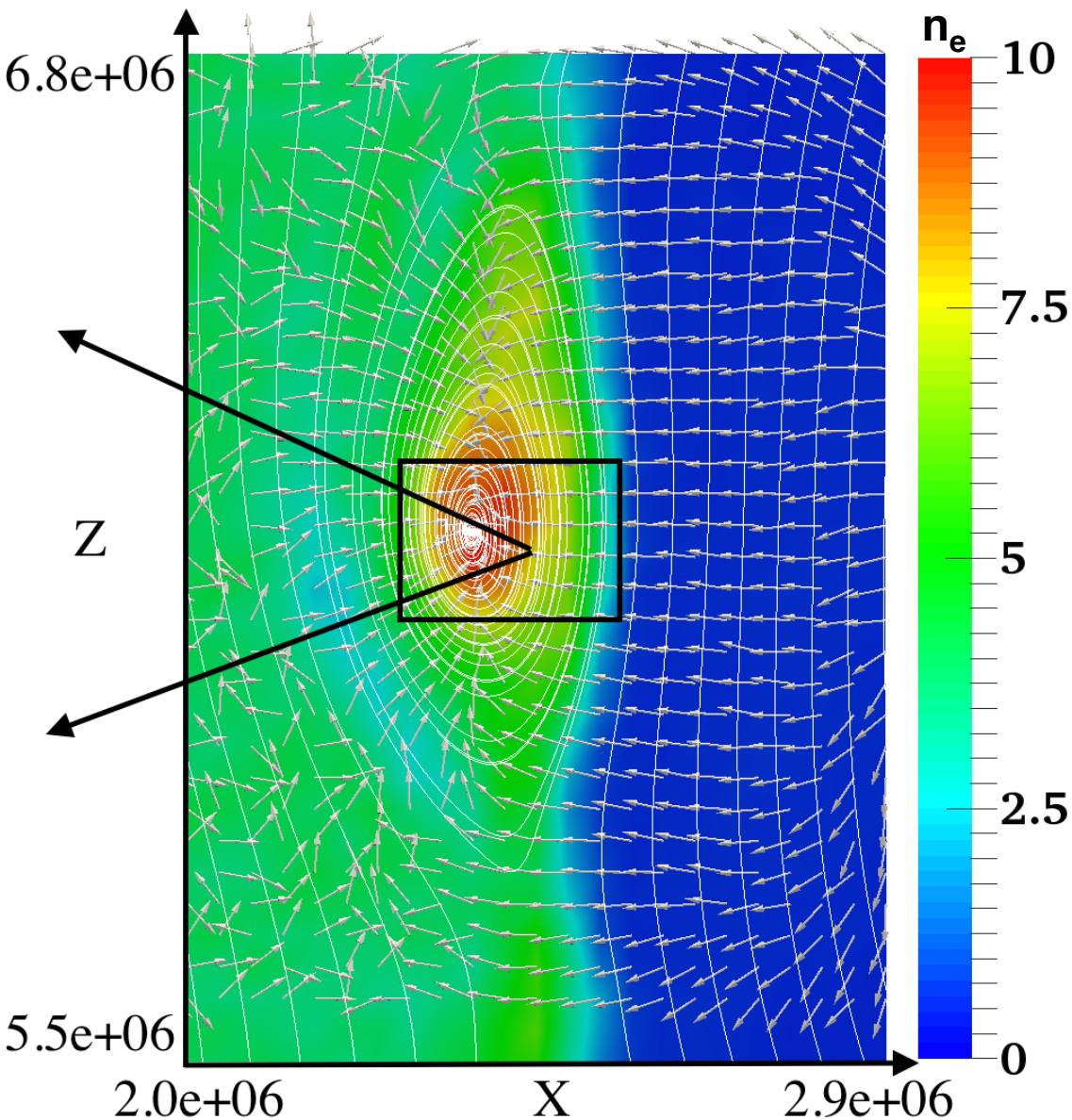
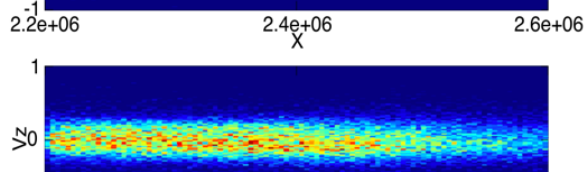
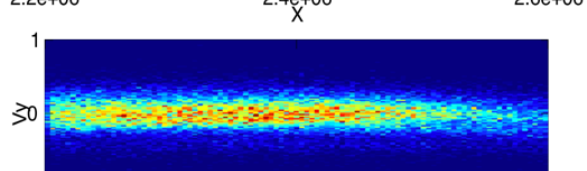
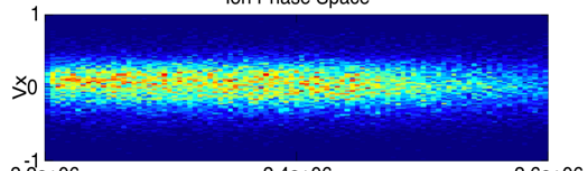
Particle distribution inside a flux rope



Electron Phase Space

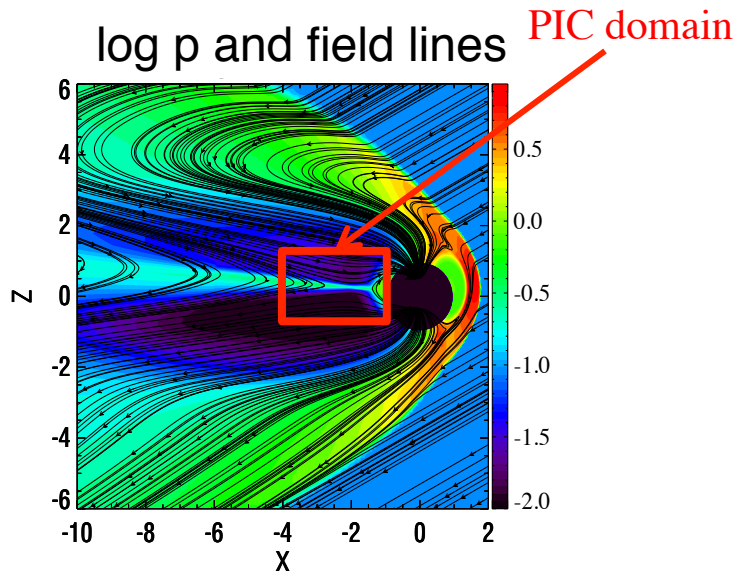


Ion Phase Space



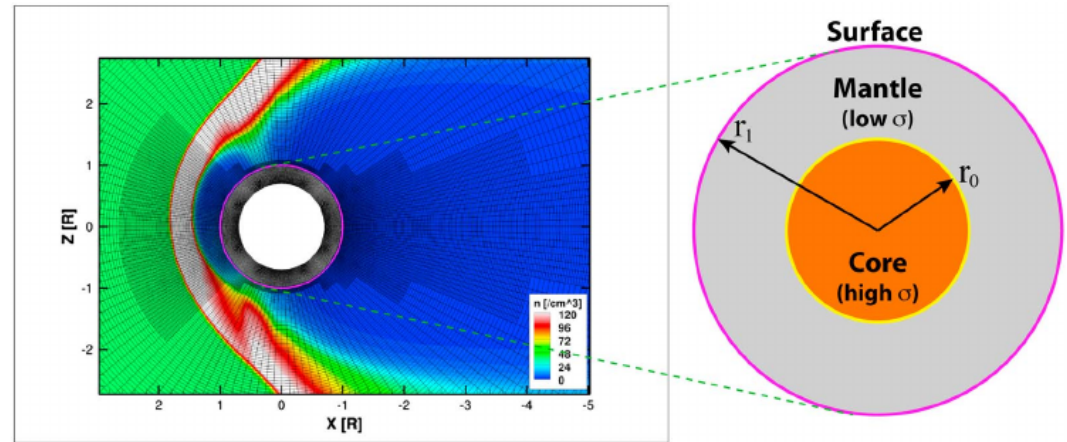


Mercury Simulation with MHD-EPIC



Hall MHD

Stretched spherical grid and resistive body

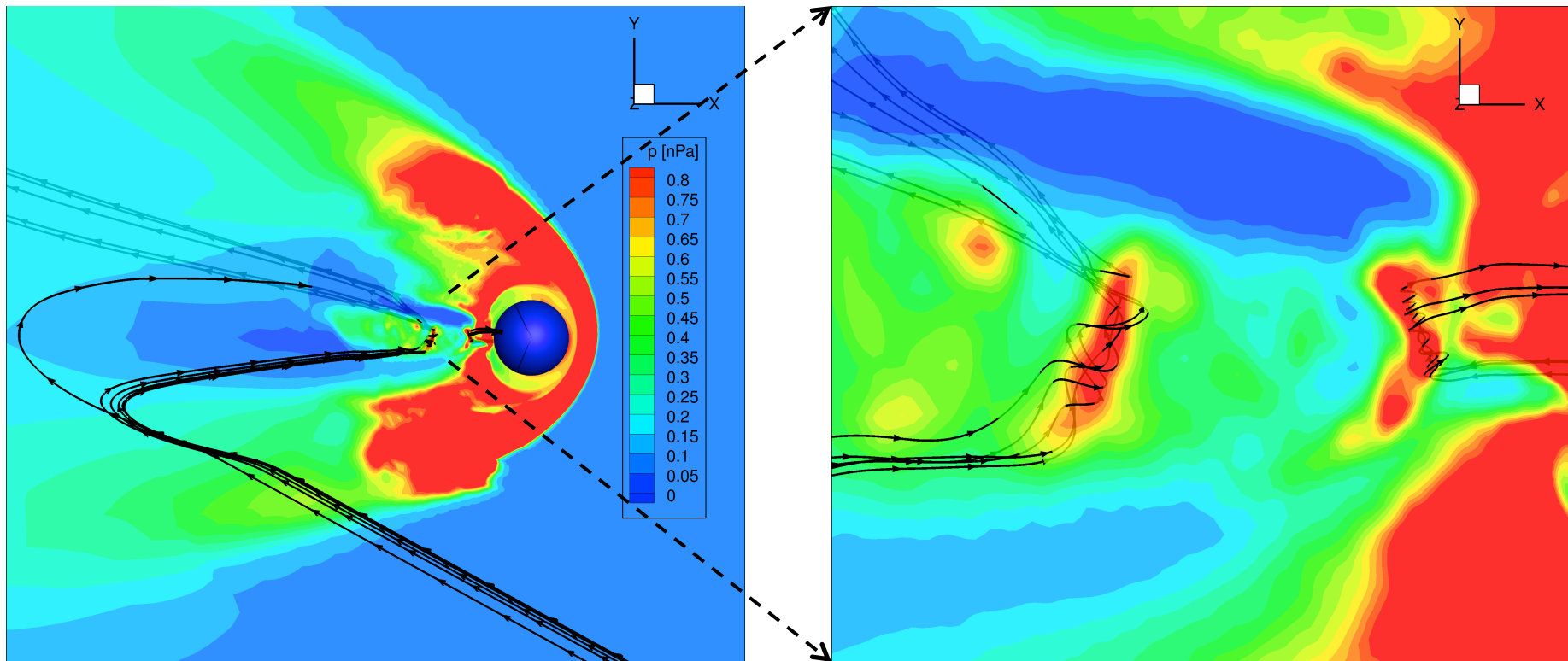


MHD-EPIC



- Both tailward and planetward flux ropes are observed.
- The tailward flux rope extends from $y = -0.4R_M$ to $y = 0.4R_M$.

Pressure with field lines

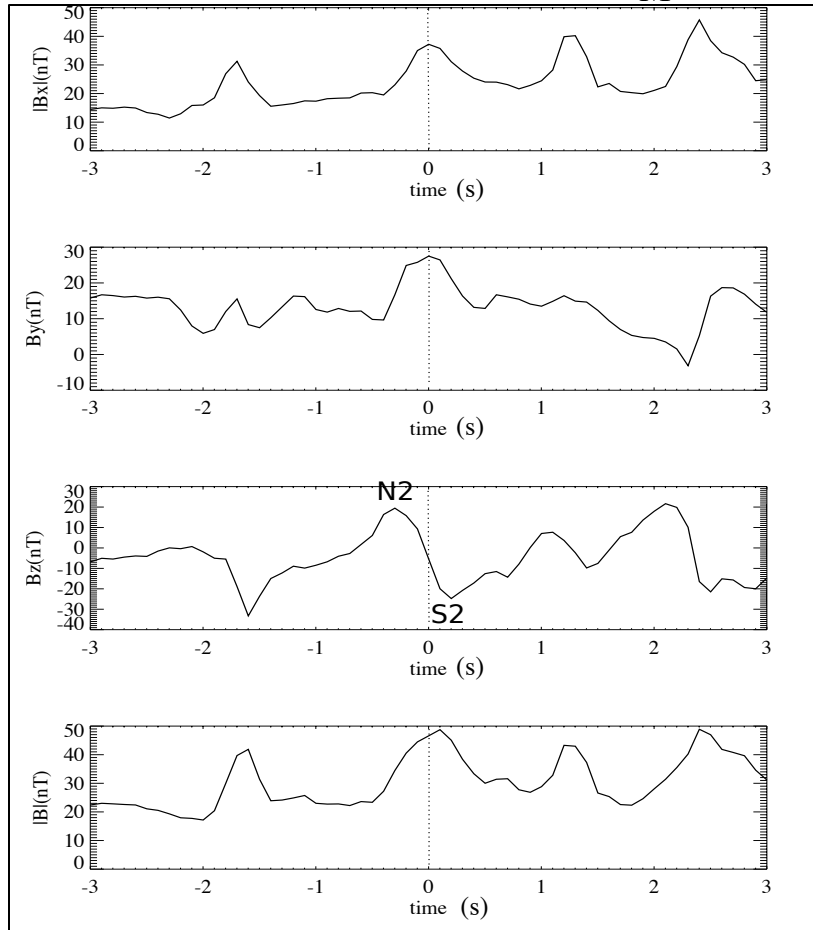




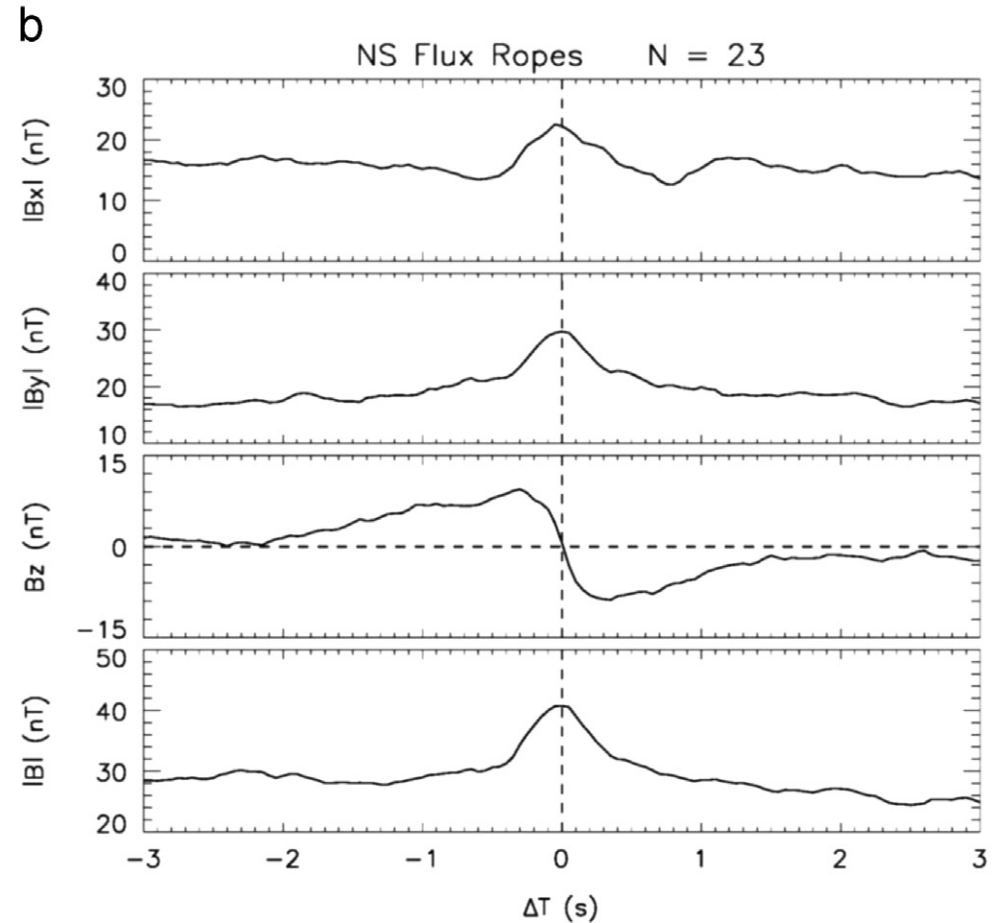
Flux Rope Signatures



Simulated tailward plasmoid at
 $(-2.11, -0.026, 0.273)R_M$



MESSENGER observation: average of
23 plasmoids (DiBraccio et. al., 2014)

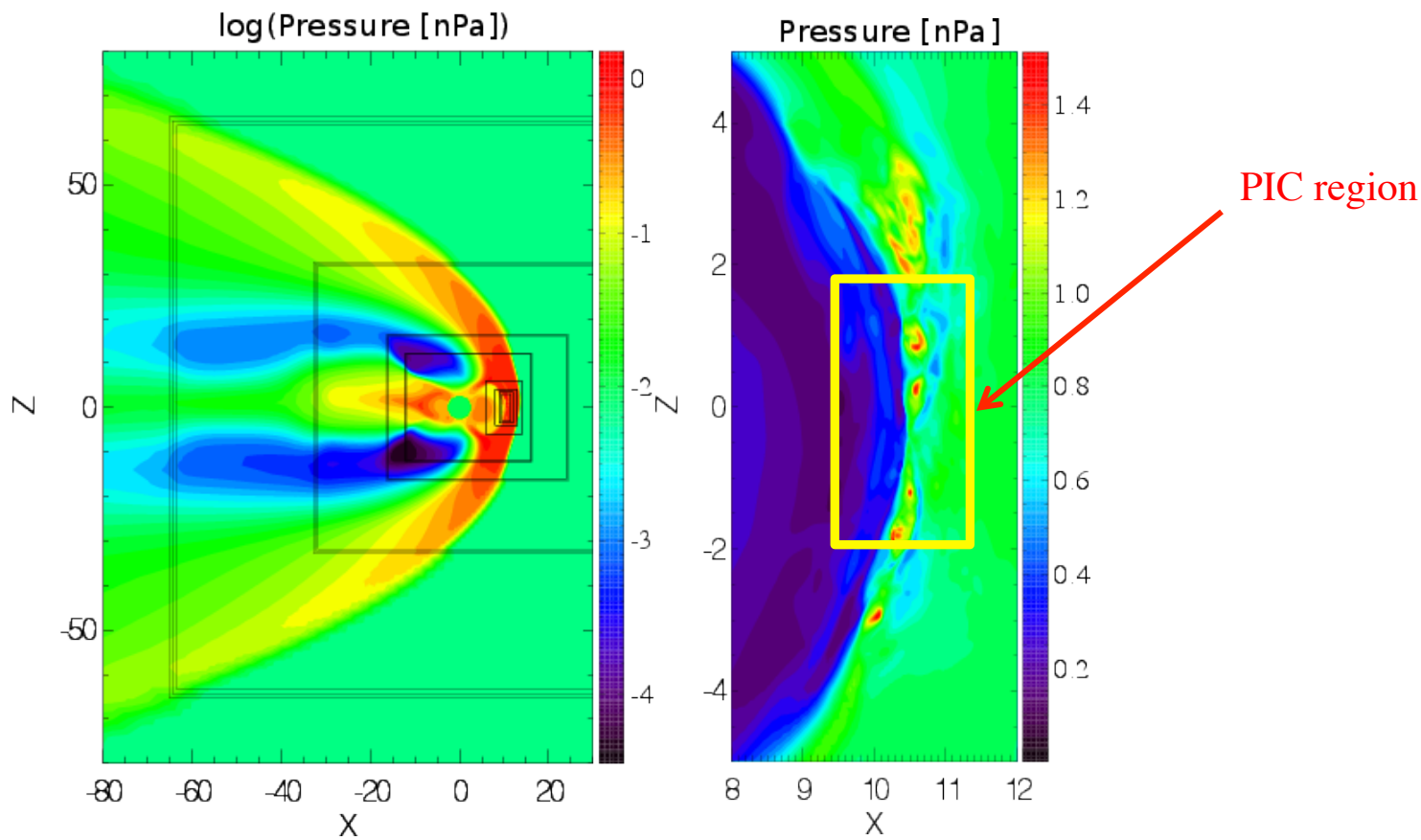




First 3D Earth Simulations with MHD-EPIC



- Dayside reconnection covered with $2R_E \times 6R_E \times 4R_E$ PIC region
- Ion mass $16m_p \rightarrow$ inertial length $\sim 1/25R_E \rightarrow 1/60R_E$ grid:
 - 31 million BATS-R-US grid cells
 - 10 million iPIC3D cells with 4.4 billion macro-particles
- 1 min simulation uses 5000 core hours: 71% iPIC3D, 27% BATS-R-US
- We are working on doing longer runs





Summary



M MHD-EPIC

- Multiple PIC regions inside extended MHD model on arbitrary grids.

M Ganymede Results (Toth et al. JGR 2016)

- Several successful simulations with 1, 2 and 4 PIC regions.
- Varied grid resolution ($1/64 R_G$), ion temperature ...
- Hall MHD and MHD-EPIC solutions look similar overall, but there are some significant differences
- Hall MHD solution is more sensitive to grid resolution
- MHD-EPIC solution shows good agreement with Galileo observations (FFT and FTE)

M Mercury Results

- PIC region around tail reconnection inside stretched spherical MHD grid
- Initial results show tailward and planetward moving fluxropes
- Simulated fluxrope signatures are similar to MESSENGER data.

M Earth Results

- First simulations with dayside PIC region. Results are promising.